Origins of the Kuroshio and Mindanao Current

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LONG-TERM GOALS

The boundary currents off the east coasts of the Philippines and Taiwan are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) flows into the Philippine coast and bifurcates into the northward Kuroshio Current (KC) and the southward Mindanao Current (MC). Quantifying these flows and understanding their dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the KC and MC can significantly impact variability downstream. For example, the KC penetrates through Luzon Strait into the South China Sea and onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave propagation. OKMC incorporates observation, theory, and modeling to make fundamental advances in our knowledge of the origins of the Kuroshio and Mindanao Currents.

OBJECTIVES

The overarching goal of OKMC is to quantify patterns of flow and fluxes of mass, heat, and salt, for the ultimate purpose of establishing predictability. We have three major research themes in OKMC:

- Transport and flow patterns
- Temperature/salinity properties and modifications

- Eddies and their effect on mean flow

This report covers contributions to these themes from forward and assimilative modeling efforts at Scripps Institution of Oceanography (SIO). Specific objectives for this period include:

- Establish the regional mean and variability of currents and water properties.
- Establish the importance of eddy forcing on the mean poleward western bundary current flow.
- Provide targets for studies of predictability.

APPROACH

The numerical approaches aid interpretation of the observational findings and explore the predictive capabilities of regional models. To provide a space–time context for the OKMC observations, a series of 1-month ocean state estimates were calculated for the period of 2010–2011 using the MIT general circulation model (MITgcm). A forward simulation of the Parallel Ocean Program (POP), a general circulation ocean model, was used to explore eddy-mean flow interactions in the OKMC region. As well, it provided depictions of the circulation and water types in this region for periods of at least 10 years. While the former approach provides a dynamical representation of the circulation for the period of the experiment, the latter provides a means a statistical means to explore causality.

WORK COMPLETED

State Estimation

The MITgcm 4D-Var state estimation, using satellite sea surface height (SSH) and temperature (SST) together with temperature and salinity profiles from floats and gliders, was run through a two-year period (2010 - 2011) in one-month segments. The optimized state from the end of the each segment was used to initialize a forecast for one month using climatological forcing, open boundary conditions, and run-off fluxes. Each monthly state estimate and forecast was compared to observations to assess the model performance of each of them. The state estimates were run a number of times, experimenting with the duration of the assimilation window (one or two months), the viscosities of the forward and adjoint runs, and the expected uncertainties of the observations. The viscosity of the forecast runs was also varied, showing that higher viscosities produced better long-term prediction errors at the expense of larger short-term errors. Maps of SSH prediction error for different forecast periods have been constructed and show that the state estimate improves the forecasts of SSH near the Philippine coast, where it is expected to influence the boundary transport. We also constructed a composite map of SSH prediction error from all monthly forecasts and showed that the prediction error increases over time as expected. We checked the non-assimilated model simulations and the state estimates against the mapped Argo data from Gilson and Roemmich to look for biases in salinity on isopycnals, and found that there are no large offsets.

We are in process of writing up the forecast skill and the results from sensitivity calculations for the 1/6-degree regional domain of the Northwest Pacific Ocean, which has significant nonlinearity in places. The state estimates for the OKMC region are being compared against estimates and sensitivities in the Philippine Sea, which is much more strongly nonlinear but still shows good hindcast and forecast performance.

Forward Modeling

Mesoscale eddies propagate westwards from the interior of the Pacific Ocean to interact with the low-latitude KC. To understand the importance and variability of eddy forcing on the mean KC, due both to these westward propagating mesoscale eddies as well as jet instabilities, full vorticity budgets were constructed from a strongly eddying (nominal 0.1°) global Parallel Ocean Program (POP)/CICE (sea ice) simulation forced with synoptic interannually varying atmospheric reanalysis fluxes.

Terms from the POP horizontal momentum equation were accumulated during the model run at every time step and archived as daily averages for the last five years (2005–2009) of the 60-year POP/CICE simulation. The momentum balance for the five-year mean was then computed offline from these time-averaged model outputs and subsequently, also the three-dimensional, time-mean vertical vorticity balance. Momentum covariance terms were also accumulated during the model run at every time step, along with standard state variables, that were archived as daily averages, allowing for the calculation of the eddy vorticity forcing terms. Collectively, these terms are known as the eddy vorticity flux convergence (EVFC). The budgets were constructed over the upper 75 m of the water column for a region encompassing waters to the east of northern Luzon and Taiwan, and in the Luzon Strait. The depth range was chosen to maximize eddy-mean flow interactions; it coincided with the depths where both the eddy kinetic energy values to the east of the Kuroshio and the strength of the current's core was significantly higher than deeper values.

Eddy forcing of the Kuroshio Current is strongest to the north of 18°N; the positive/negative dipole EVFC pattern in the east/west direction to the north of the Philippines in the Luzon Strait (~20°N), implies a deceleration of the KC on its eastern flank (Figure 1). Examination of all terms in the vorticity budget along 20°N between 120.5°E and 122.5°E, showed that the leading-order balance was between the mean and eddy horizontal advection of relative vorticity terms. This balance indicates that horizontal eddy forcing of the mean flow is the dominant forcing at this latitude. No topographic sidewall effects were present either along or nearby this section. However close to topography, such as along 18.75°N between 122°E and 123°E, the horizontal eddy forcing term was of the same magnitude as a broader range of terms including the horizontal diffusion of relative vorticity and the pressure torque term. These results, together with those from seasonal vorticity budgets, are in preparation for publication.

Integrative Studies

Model output from both the MITgcm (state estimates and a forward simulation) and POP (forward run) were used together with OKMC and other observations to obtain an integrative understanding of the mean and variability of the circulation and water masses in the Mindanao Current/Undercurrent (MC/MUC). Maps of salinity on isopycnals were used to examine water mass variability in the MUC and nearby vicinity. Over potential density range 23.5 to 24 kg/m^3, the MITgcm state estimate (Figure 2) shows a decrease in the subsurface salinity maximum of North Pacific Tropical Water (NPTW) as it is advected along the coast, in agreement with glider data. These results are part of a submitted manuscript led by Martha Schonau (SIO). Another manuscript that is accepted for publication with minor revision by Qiu et al., focuses on the North Equatorial Current/Undercurrent System (NEC/NEUC). The POP model was used to study the temporal variability of the NEUC jets (crossing the glider line: 134.5°E between 8° and 20°N) on scales from intraseasonal through interannual.

Gliders

Gliders were used to observe the NEC and the Mindanao Current. Two Sprays were deployed from Palau every 4-5 months, one that proceeded northward across the NEC, and one that headed westward towards the MC. Operations commenced in June 2009 and have continued uninterrupted. The data set included 24 glider missions. To date, we completed 21 crossings of the Mindanao Current, and 20 sections across the NEC. In total, the gliders did over 12,000 dives, and covered over 53,000 km in 3000 days. The final recovery occurred in January 2014. The first publication from this work addressed the NEC (Schönau and Rudnick, 2015).

Floats

Ten floats were deployed in August 2011 from the Japanese R/V Mirai. Data from these floats are processed through the Argo system, and are made available through GTS to modeling centers including NAVO. An additional 17 floats obtained through a DURIP were deployed in March 2013 from the R/V Mirai. Of the 27 floats deployed, all but one returned data. Analysis of these data is in collaboration with Bo Qiu of U. Hawaii, with the first publication addressing distinct cores of undercurrent beneath the NEC (Qiu et al., 2013), and the second addressing subthermocline circulation throughout the low latitude northwestern Pacific (Qiu et al., 2015).

Drifters

To enhance the historical near surface current data in the study area, deployments of surface drifters from the merchant vessels from Kaohsiung to eastern Australia were performed. The deployment locations were chosen from the analysis of the historical drifter dataset in order to sample the seasonal variability of the flow at the roots of the KC and of the MC. Professor Ruo-Shan Tseng at National Sun Yat-sen University was local contact point in Taiwan to store, prepare and deliver the drifters to the ship. The drifter deployments were completed in 2013. In total, we have deployed 268 SVP drifters in the OKMC region from August 2010 through August 2013 (255 from VOS and 13 in Lamon Bay from the R/V Revelle).

RESULTS

Our most important results are as follows:

- Predictability of the SSH near the boundary using the state estimate has skill greater than persistence at time lags of a few weeks.
- Mesoscale eddies are of leading order importance in the forcing of the mean KC in Luzon Strait; eddy effects are most pronounced away from the effects of side-wall topography.
- The salinity maximum of the North Pacific Tropical Water is a useful tracer throughout the region. The MITgcm model simulations show a tongue of salinity that resembles the glider observations in the MC. Calculations are underway to infer mixing properties from the salt budget.

IMPACT/APPLICATIONS

The boundary current region is tractable for model analysis and prediction based on ocean state and atmospheric forcing.

RELATED PROJECTS

Related projects include an ongoing Early Student Support grant and a completed DURIP. This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

PUBLICATIONS

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Schönau, M. C. and D. L. Rudnick, 2015: Glider observations of the North Equatorial Current in the western tropical Pacific. *Journal of Geophysical Research*, **120,** 3586–3605, doi: 10.1002/2014JC010595.

Schönau, M.C., D. L. Rudnick, I. Cerovecki, G. Gopalakrishnan, B. D. Cornuelle, J. L. McClean, B. Qiu, The Mindanao Current: mean structure and connectivity, *Oceanography*, accepted with moderate revision.

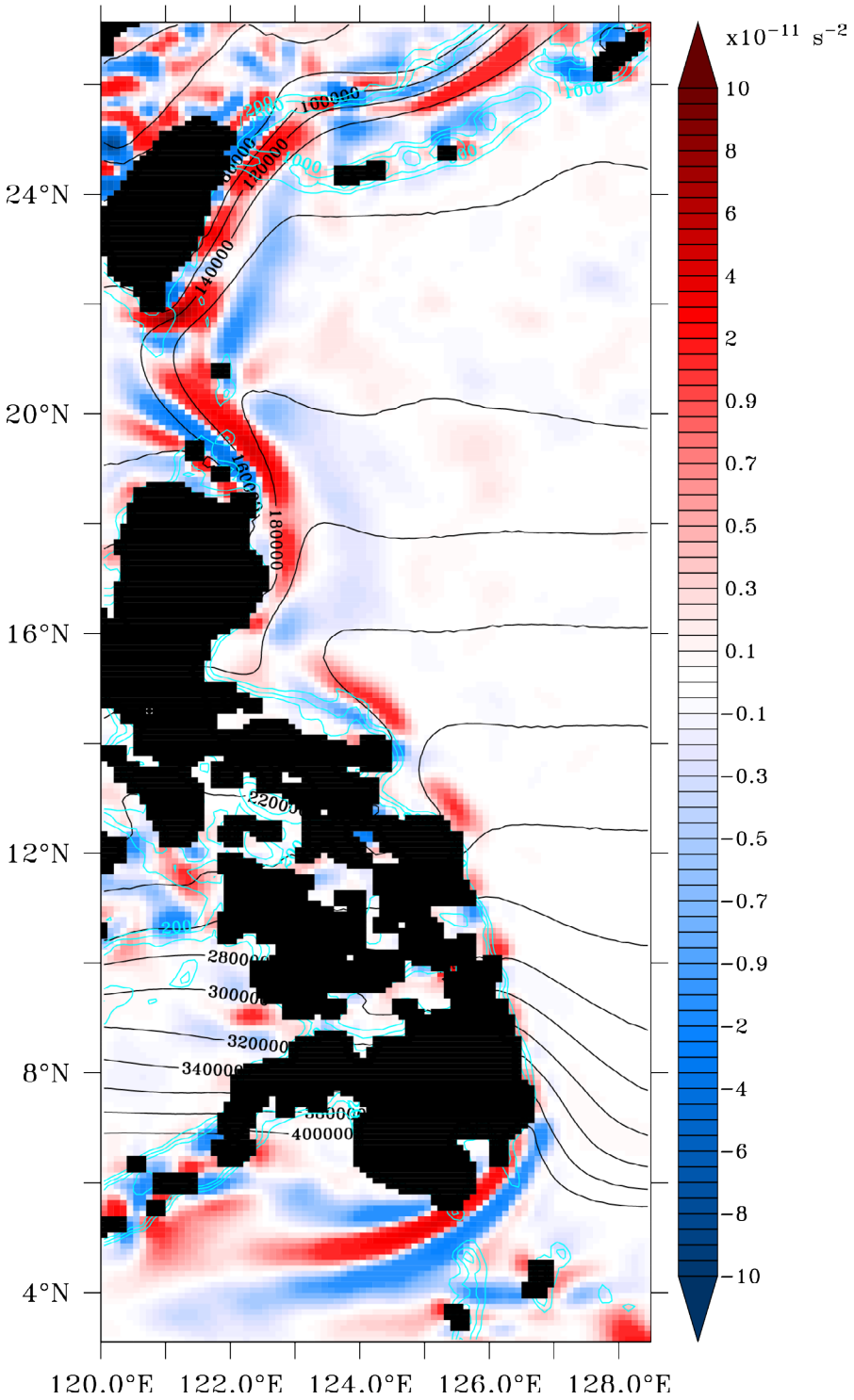

Figure 1: Mean eddy vorticity flux convergence (x 10^{-11} s^{-2}, color contours) over the top 76 m of the water column for 2005-2009 from global 0.1° POP/CICE. Black contour lines are barotropic streamlines (m^2 s^{-1}) and the model bathymetry contours (m) are in cyan. Eddy forcing of the Kuroshio Current (KC) is strongest to the north of 18°N; the positive/negative dipole pattern in the east/west direction to the north of the Philippines in the Luzon Strait (~20°N), implies a deceleration of the KC on its eastern flank.

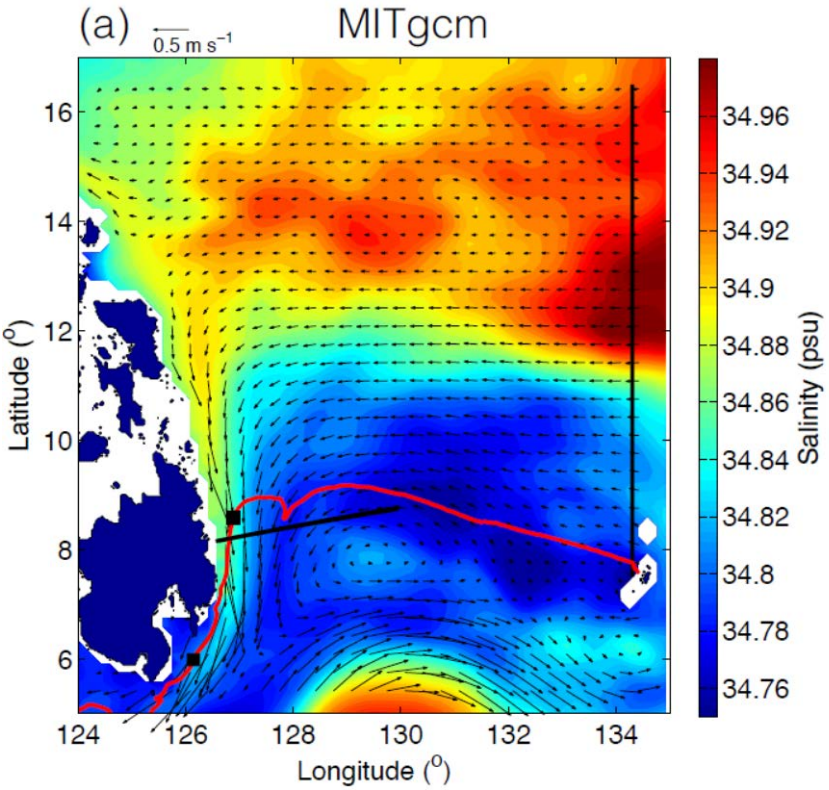

Figure 2. Advection of North Pacific Tropical Water (NPTW) shown on horizontal map of velocity (arrows) and salinity (color) averaged over potential density range 23.5 to 24 kg/m^3 from the MITgcm optimized solutions for the period 2010 – 2011. There is a decrease in the subsurface salinity maximum of NPTW as it is advected along the coast.